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Objective and Subjective Effects of Passive Exoskeleton on Overhead Work

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I. Introduction

Work-related musculoskeletal disorders (MSDs) are the first cause of occupational disease in developed countries and therefore represent a major health issue [1]. MSDs develop when biomechanical demands exceed the worker's physical capacity. In this regard overhead work is often cited as a MSDs risk factor [2, 3]. Overhead work yet remains very common on assembly lines, especially in the automotive industry. Indeed many complex tasks cannot be fully automatized because they still require human cognitive skills. One solution to relieve workers while keeping them in control of the task execution is then to assist them with an exoskeleton [4].

Recently several industrial exoskeletons have been developed to support arms and/or tool weight during overhead tasks [5–11]. Many of them showed promising results regarding the reduction of physical workload. However, these studies present only partial assessments of the benefit provided by the exoskeletons. They exclude some important aspects like side-effects, adaptation, or user acceptance. In this work we present an exhaustive assessment of a novel passive exoskeleton for overhead work.

II. Method

The benefit provided by the use of an exoskeleton cannot be assessed solely based on the reduction of effort in the targeted limb. An exoskeleton is a wearable device, therefore its use might disrupt human movements or require additional effort. Supplemental effort can be caused by the weight of the device or, with passive exoskeletons, by the transfer of force from one joint to another. In addition, users' opinion of the device also affects its effectiveness. An exoskeleton that is ill-perceived by the user might remain unused, or cause psychological stress if use is imposed. Therefore we propose an assessment process that addresses the following aspects:

- *Task performance:* The task performance should be at least as good with the exoskeleton as without it.
- *Fatigue:* The exoskeleton should reduce metabolic demand and delay the apparition of fatigue.
- *Physical effort:* The exoskeleton should relieve the limb that is directly impacted.
- *Side-effects:* The exoskeleton should not significantly increase effort in limbs that are not directly impacted, nor cause bad postures.
- *Adaptation:* Using the exoskeleton should not require a long training nor cause after-effects at removal.
- *Acceptance:* Users should feel better when using the exoskeleton compared to when not using it.

A. Exoskeleton Description

Within the European project AnDy [12], the provided exoskeleton prototype is an upper-limb passive exoskeleton intended for supporting the weight of the arms, and possibly of manipulated tools, while the user is working overhead. This exoskeleton does not enhance the human's strength, but renders his/her arms virtually weightless, thereby relieving the shoulder joint. Being passive, hence without motors, the exoskeleton is light, not bulky, and easy to wear.

B. Experiment

Twelve participants performed an overhead pointing task with a portable tool, with and without the exoskeleton (Fig. 1). The participants' physical and physiological state was monitored with whole-body inertial motion capture, ground reaction force, EMG on shoulder and back muscles (right anterior deltoid and right erector spinae longissimus), oxygen consumption, and heart rate. The tool motion was recorded with optical motion capture to evaluate accuracy and completion time. Following the experiment, the perceived workload was assessed with the NASA Task Load Index (NASA-TLX) [13]. In addition, participants answered a questionnaire and a semi-directed interview was conducted to evaluate technology acceptance.

C. Measures

a) Task performance: Task performance was assessed with the movement accuracy and completion time.

b) Fatigue: Oxygen consumption and heart rate were used to evaluate objective metabolic demand and fatigue, while the NASA-TLX indicated subjective fatigue. Evolution of task performance over time was used as an additional indicator for fatigue.

c) Physical Effort: Given that the exoskeleton aimed at supporting the arms weight, the shoulder joint was directly impacted by the use of the exoskeleton. Therefore, activation of the anterior deltoid and estimated shoulder torque were used to assess the physical demand on the impacted limb. Joint torques were computed with inverse dynamics based

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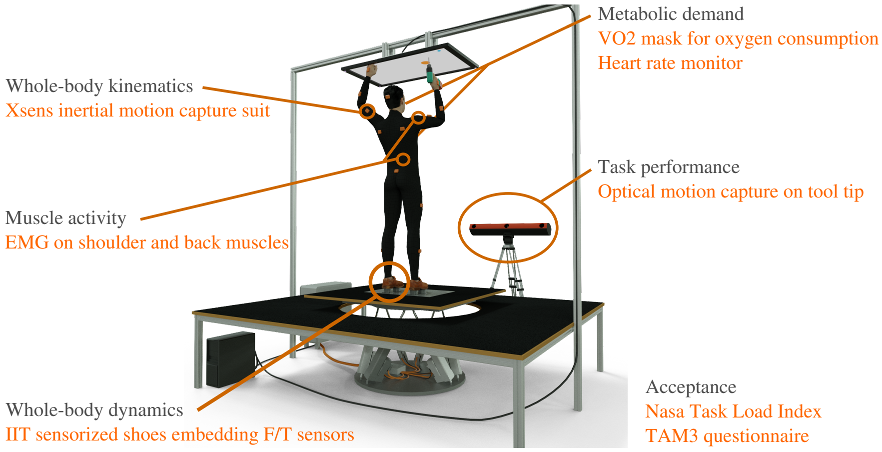

Fig. 1. Experimental set-up and sensors used to assess the exoskeleton.

on the recorded whole-body kinematics and ground reaction force [14].

d) Side-effects: Activation of erector spinae and back and hip torques were used to assess potential increase in effort in non-directly impacted limbs. Joint angles obtained by whole-body kinematics served to evaluate postural changes.

e) Adaptation: The tool 3D trajectory as well as trajectories of the shoulder, elbow and back in joint space were used to compare movement strategy with and without the exoskeleton. Evolution of task performance over time was used to detect learning and after-effects.

f) Acceptance: Score obtained in the technology acceptance questionnaire was used to quantitatively assessed acceptance of the exoskeleton, while opinions expressed during the interview served to shed light on some of the questionnaire answers.

III. Results

Comparison of the two conditions with and without exoskeleton revealed that muscle activation, oxygen consumption and heart rate were significantly reduced when using the exoskeleton. Conversely, task performance was affected neither positively nor negatively. Importantly, the reduction in overall workload observed with objective measurements was also observed in subjective measurements: the task not only was, but also felt, less demanding when wearing the exoskeleton. Eventually, acceptance score was high and participants all said that they would choose to use the exoskeleton again for such a task.

IV. Conclusion

Future work will be directed towards evaluating the exoskeleton on different tasks, including bending, crouching and walking to assess its transparency and potential disturbances of the users movements. Experiments on industrial sites are also planned. Furthermore, results from the evaluation will serve to guide the development of an intuitive adaptation of the level of support provided by the exoskeleton.

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